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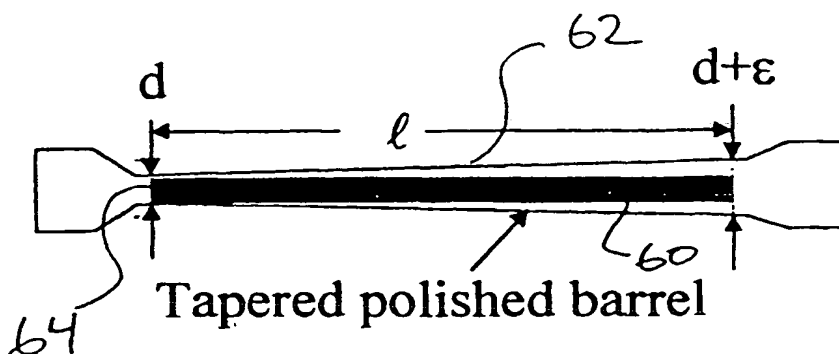
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ning of each regular issue of the PCT Gazette.

(54) Title: TAPERED LASER ROD



(57) Abstract: Laser rods with polished barrels and flanged end caps have found increasing application in diode array end-pumped laser systems. The polished barrel of the rod serves to confine diode array pump light within the rod. In systems utilizing an end-pumping geometry and such polished barrel laser rods, the pump light that is introduced into one or both ends of the laser rod, is ducted down the length of the rod via the total internal reflections (TIRs) that occur when the light strikes

the rod's barrel. A disadvantage of using polished barrel laser rods is that such rods are very susceptible to barrel mode paths that can trap spontaneous emission over long path lengths. This trapped spontaneous emission can then be amplified through stimulated emission resulting in a situation where the stored energy available to the desired lasing mode is effectively depleted, which then negatively impacts the laser's performance, a result that is effectively reduced by introducing a taper onto the laser rod.



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TAPERED LASER ROD

This application claims priority to Provisional Patent
Application Serial No. 60/156,279, titled "Tapered Laser Rods as a
5 Means of Minimizing the Path Length of Trapped Barrel Mode Rays,"
filed September 27, 1999, incorporated herein by reference.

The United States Government has rights in this invention
pursuant to Contract No. W-7405-ENG-48 between the United States
Department of Energy and the University of California for the
10 operation of Lawrence Livermore National Laboratory.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to means for improving laser
performance through reduction of amplified spontaneous emission
15 (ASE), and more particularly, it relates to the use of a flanged and
tapered laser rod to limit the maximum ray paths that can be trapped
within the laser rod.

Description of Related Art

As early as 1965, reports in the literature discuss the impact
20 of trapped light in polished barrel laser rods (J. Linn and J. Free, "Effect

of Trapped Light on the Output of a Ruby laser," Applied Optics, 4, p
1099, 1965). The established picture of trapped laser light 10 in a
polished barrel laser rod 12 is shown in Figure 1. Nearly all laser rods
employed in laser systems today incorporate fine grind on the side
5 surfaces of the laser rod to disrupt and scatter the barrel modes. The
new approach described herein functions with an optical polish on the
side surfaces of the laser rod and instead sweeps the barrel mode light
to the one of the ends of the laser rod, where it is ejected.

Trapped by total-internal-reflection (TIR), light can swirl
10 around the inside of the laser rod and travel over long path lengths
before reaching the end of the rod. The result of these long trapped
ASE paths is that the gain present in the outer portion of the laser rod
can be effectively depleted. If n_r is the refractive index of the laser rod
and n_s is the refractive index of the material surrounding the laser rod,
15 then it can be shown that the annular portion of the rod swept out by
these swirling rays is given by $(n_s/n_r) r_{rod} < r < r_{rod}$. This means that if
the gain depletion is severe, then only that portion of the rod lying
inside a circular area with radius $(n_s/n_r) r_{rod}$ is useful for extracting
laser energy from the rod. Figure 2 illustrates the useful laser energy
20 extraction area 20 and the unusable area 22.

As an example, consider a YAG rod surrounded by water for
cooling, where $n_r=1.82$ and $n_s=1.33$. In this case, if the swirling rays

cause severe gain depletion, then only that portion of the rod contained within the central 53% ($=100(1.33/1.82)^2$) of the rod's cross sectional area would be useful for contributing to laser output power.

One technique that has recently been developed and demonstrated, the flanged end-capped laser rod See U.S. Patent No. 5,936,984, "Laser Rods With Undoped, Flanged End-Caps," by Helmuth Meissner et al., incorporated herein by reference), has proven useful in limiting the maximum length of the ray path that can be trapped in the laser rod. In the case of the straight barrel polished laser rod shown in Figure 1 above, if the swirling rays of light wander to the end of the laser rod and then strike the end face of the rod at a high angle, they will be completely trapped by total internal reflection at that end face. In such a situation, the rays will be simply turned around and sent swirling down the rod in the other direction until they hit the output face at that end. This process is particularly bad from the viewpoint of depleting the stored laser energy in the rod, as these trapped rays now have an infinitely long trapped path length.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a technique for reducing the ability of the trapped spontaneous emission to negatively impact laser performance through amplified spontaneous emission (ASE).

It is another object of the invention to provide a tapered laser rod having flanged endcaps to dramatically reduce the maximum trapped path length of barrel modes within the laser rod.

These and other objects of the invention will be apparent to those skilled in the art based on the teachings herein.

A flanged endcap effectively traps the swirling ASE rays, causing them to be scattered out of the laser rod. However, limiting the trapped ray paths to one pass down the length of the laser rod can still allow for very long ray paths to be trapped, causing gain depletion in the laser rod. The present invention limits the maximum ray paths that can be trapped within the laser rod by tapering the laser rod over its length. This tapered design combined with flanged endcaps eliminates deleteriously long trapped path lengths.

Tapering the diameter of the laser rod over its length thus reduces the maximum trapped path length of barrel modes, reducing the ability of the trapped spontaneous emission to negatively impact laser performance through amplified spontaneous emission. In the present invention, a laser rod incorporates both undoped flanged endcaps and a tapered barrel.

In one embodiment, the rod barrel tapers in diameter from a small value of at one end to a larger value at the other end. By introducing a taper on the barrel of the laser rod, swirling rays are

prevented from loitering for extended path lengths in the laser rod.

This is a significant improvement over the use of the flanged endcaps on a straight barreled rod, as the straight barrel rod configuration still allows trapped paths with infinite length.

5 Due to the rod's taper, there is a portion of the laser rod's volume that will be inaccessible to an extracting laser beam due to the aperture introduced by the small end of the laser rod. Because this inaccessible volume grows as the taper grows, there will be an optimum taper value.

10 In another embodiment, the center of the laser rod is the narrowest and the diameter increases towards either end. The advantage of this geometry, with its dual taper, over a rod with a continuous taper from one end to the other, is that the maximum trapped path length in this rod is halved compared to that in the
15 continuously tapered rod.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates swirling rays propagating to the end of a barrel laser rod.

20 Figure 2 illustrates the useful laser energy extraction area and the unusable area.

Figure 3 shows a diagram of a straight barreled laser rod having a flange on each end.

Figure 4 shows a sketch of a laser rod incorporating both undoped flanged endcaps and a tapered barrel.

5 Figure 5 illustrates that in the use of the method of images, rays are straight-line propagated through reflective interfaces into image regions that are constructed from the original laser rod through the use of repeated reflections of the gain volume at the TIR surfaces.

Figure 6 shows the central area of the rod that can be
10 extracted with a laser beam in a conventional resonator.

Figure 7 shows the center of the rod is the narrowest and the diameter increases as you go towards either end.

Figure 8 shows the maximum trapped ASE path length versus taper in rod diameter over the rod length.

15 Figure 9 shows the fractional volume of the rod that is extractable versus taper in rod diameter over the rod length.

DETAILED DESCRIPTION OF THE INVENTION

The present inventors have discovered that once the swirling rays shown Figure 1 reach the end of the barrel laser rod, the
20 placement of a flanged endcap will effectively trap the rays and they will be scattered out of the laser rod. Figure 3 shows a diagram of a

laser rod 30 having a flange 32 on each end. Such configuration has been shown to be effective at limiting the maximum ray paths that can be trapped in the laser rod.

Effectively, the flanged laser rod limits the swirling rays described above to at most one pass down the length of the laser rod. However, even limiting the trapped ray paths to one pass down the length of the laser rod can still allow for very long effective ray paths to be trapped, which in turn can pose a serious problem for gain depletion in the laser rod. These long trapped ray paths are characterized by swirling around many times while only moving a very short transverse distance up or down the laser rod. In fact, it is still possible for infinitely long ray paths to exist, which swirl around the laser rod but do not walk up or down its length.

The present invention limits the maximum ray paths that can be trapped within the laser rod by tapering the laser rod over its length. This tapered design combined with the use of the flanged endcaps described above results in the elimination of the possibility of infinitely long trapped path lengths.

Tapering the diameter of the laser rod over its length dramatically reduces the maximum trapped path length of a barrel mode, thereby reducing the ability of the trapped spontaneous emission to negatively impact laser performance through amplified

spontaneous emission (ASE). Figure 4 shows a sketch of a laser rod incorporating both undoped flanged endcaps and a tapered barrel, which is the subject of the presently disclosed invention.

In Figure 4, the rod barrel 40 tapers in diameter from a small value of d at one end to a larger value of $d+\epsilon$ at the other end 44. The impact of introducing a taper on the barrel of the laser rod is that it prevents swirling rays from loitering for extended path lengths in the laser rod. This is a significant improvement over the use of the flanged endcaps on a straight barreled rod, as the straight barrel rod configuration still allows trapped paths with infinite length. To estimate the maximum path lengths that can be trapped by a tapered laser rod with endcaps, a simple "method of images" technique can be invoked that greatly simplifies the calculation. The reason for using the method of images trick is that it simplifies the calculation of ray paths that involve TIR. Using the method of images, rather than having to calculate reflected angles and multiple bounce paths, rays are just straight-line propagated through reflective interfaces into image regions that are constructed from the original laser rod through the use of repeated reflections of the gain volume at the TIR surfaces. Of course, using this method does require that the constructed image space be continuous in the sense of not containing any internal gaps. Unfortunately, round cross-sectioned rods do not meet the requirement of continuously filling a region of space on reflection

about their various TIR surfaces. One simple approximation that allows the method of images to be applied to round rods models them as having a hexagonal cross-section. Under this approximation, a rod with a taper generates a spherical shell with thickness equal to the length of the rod.

In Figure 5, the longest path length that is trapped in the laser rod is then the length of the longest line that can be drawn between any two points on the surface of the sphere. In the figure, a ray which intersects the surface of the sphere corresponds to a trapped ray which has wandered into the flanged endcap at the rod end with the largest diameter. With the help of Figure 5, the longest trapped ray path is seen to correspond to a line that is tangent to the surface of the inner sphere. A simple calculation for the presently considered rod, with its diameter tapering from d at one end to $d+\epsilon$ at the other, then gives the length of this longest trapped path length as $2\ell\text{SQR}(1+2d/\epsilon)$, where ℓ is the length of the laser rod over which the taper occurs.

Considering this expression for the longest trapped ray length, the question that naturally arises is what is the optimum value for the taper parameter ϵ . Clearly, if ϵ approaches 0, then the maximum path length can be pushed to infinity as has already been discussed for a straight rod. On the other hand, if ϵ is made too large, then the useful

mode volume of the rod is decreased. This last point is illustrated with the help of Figure 6 as discussed below.

In Figure 6, the central area 60 corresponds to that portion of the rod 62 that can be extracted with a laser beam in a conventional resonator. Due to the rod's taper, there is a portion of the laser rod's volume that will be inaccessible to an extracting laser beam due to the aperture introduced by the small end 64 of the laser rod. Because this inaccessible volume grows as the taper grows, there will be an optimum taper value, ϵ , that best balances the contradictory requirements of maximizing the size of the taper so as to minimize the longest trapped path length, and minimizing the size of the taper so as to maximize the fractional volume in the rod that is accessible to the extracting laser beam. Figures 8 and 9 show these two quantities plotted against the taper size for a 2 mm diameter by 5 cm long Yb:YAG laser rod.

A variation on the above approach that offers some performance benefit is shown in Figure 7. Here, rather than having a continuous taper over the entire length of the laser rod 70, the center of the rod 72 is the narrowest and the diameter increases as you go towards either end.

The advantage of this geometry, with its dual taper, over a rod with a continuous taper from one end to the other, is that the

maximum trapped path length in this rod is halved compared to that in the continuously tapered rod. Additionally, this halving of the maximum trapped path length comes without a penalty in the fractional volume of the rod from which energy can be extracted, assuming the same value of taper parameter, ϵ , for both types of rods.

The foregoing description of the invention has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. The embodiments were chosen and described to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best use the invention in various embodiments and with various modifications suited to the particular use contemplated. The scope of the invention is to be defined by the following claims.

We claim:

1. An apparatus, comprising:
a polished laser rod comprising a first end and a second end,
wherein said laser rod comprises a tapered diameter;
a first flanged endcap operatively connected to said first end;
5 and
a second flanged endcap operatively connected to said
second end.
2. The apparatus of claim 1, wherein said laser rod
comprises a maximum diameter at said first end and a minimum
10 diameter at said second end.
3. The apparatus of claim 1, wherein said laser rod
comprises a maximum diameter at said second end and a minimum
diameter at said first end.
4. The apparatus of claim 1, wherein said laser rod
15 comprises a minimum diameter at about half the distance from said
first end to said second end.
5. The apparatus of claim 1, wherein said first flanged
endcap and said second flanged endcap are undoped.

6. The apparatus of claim 1, wherein said laser rod tapers in diameter from a small value of d at one end to a larger value of $d+\epsilon$ at the other end.

5 7. The apparatus of claim 1, wherein said tapered diameter is optimized to a taper value that balances the contradictory requirements of maximizing the size of said taper so as to minimize the longest trapped path length of light rays propagating within said laser rod, and minimizing the size of said taper so as to maximize the fractional volume in said laser rod that is accessible to an extracting
10 laser beam.

8. The apparatus of claim 1, wherein said tapered diameter continuously changes over the entire length of said laser rod.

9. The apparatus of claim 1, wherein said laser rod is
15 narrowest between the ends of said laser rod and the diameter increases at each end.

10. The apparatus of claim 1, wherein said laser rod is narrowest at about half the distance between the ends of said laser rod and the diameter increases as you go towards either end.

20 11. The apparatus of claim 10, wherein said tapered diameter is optimized to a taper value that balances the contradictory requirements of maximizing the size of said taper so as to minimize the longest trapped path length of light rays propagating within said laser

rod, and minimizing the size of said taper so as to maximize the fractional volume in said laser rod that is accessible to an extracting laser beam.

12. A solid state laser, comprising:

- 5 a laser rod with a first end and a second end, wherein said laser rod comprises a tapered diameter;
- a first flanged, undoped end-cap optically contacted to said first end portion to form a first interface;
- a second flanged, undoped end-cap optically contacted to
- 10 said second end to form a second interface;
- a cooling jacket sealably coupled to said first and second flanged end-caps;
- a pump laser for providing pump laser light directed at said first flanged end-cap; and
- 15 a lens duct interposed between said pump laser and said first flanged end-cap, wherein said lens duct will concentrate said pump laser light.

13. The solid state laser of claim 12, wherein said laser rod has a host lattice, and wherein said host lattice and said first and

20 second flanged end-caps are selected from the group consisting of yttrium aluminum garnet, gadolinium gallium garnet, gadolinium scandium gallium garnet, lithium yttrium fluoride, yttrium vanadate, phosphate glass and sapphire.

14. The solid state laser of claim 13, wherein said host lattice is doped with a material selected from the group consisting of Ti, Cu, Co, Ni, Cr, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm and Yb.

5 15. The solid state laser of claim 12, wherein said laser rod comprises Yb.^{sup.3+} doped YAG, and wherein said pump laser is an InGaAs diode laser array.

16. A method for fabricating a laser rod, comprising:
providing a polished laser rod comprising a first end and a second end;

10 operatively connecting a first flanged endcap to said first end;

operatively connecting a second flanged endcap to said second end; and

tapering the diameter of said laser rod.

15 17. The method of claim 16, wherein the step of tapering the diameter of said laser rod comprises forming a maximum diameter at said first end and a minimum diameter at said second end.

18. The method of claim 16, wherein the step of tapering the diameter of said laser rod comprises forming a maximum diameter at
20 said second end and a minimum diameter at said first end.

19. The method of claim 16, the step of tapering the diameter of said laser rod comprises forming a minimum diameter at about half the distance from said first end to said second end.

20. The method of claim 16, further comprising optimizing the diameter of said laser rod to a taper value that balances the contradictory requirements of maximizing the size of said taper so as to minimize the longest trapped path length of light rays propagating within said laser rod, and minimizing the size of said taper so as to maximize the fractional volume in said laser rod that is accessible to an extracting laser beam.

FIG. 1

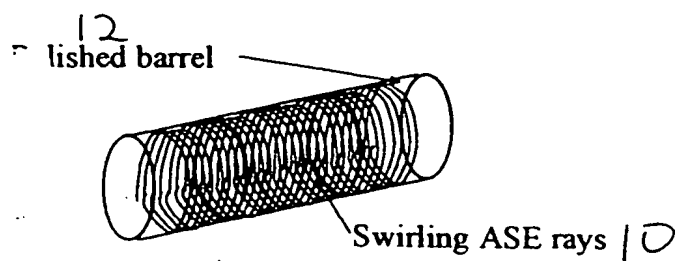


FIG 2

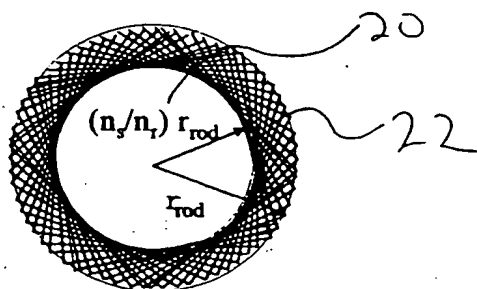


Fig 4

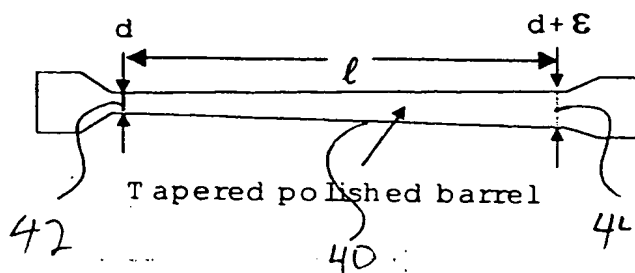
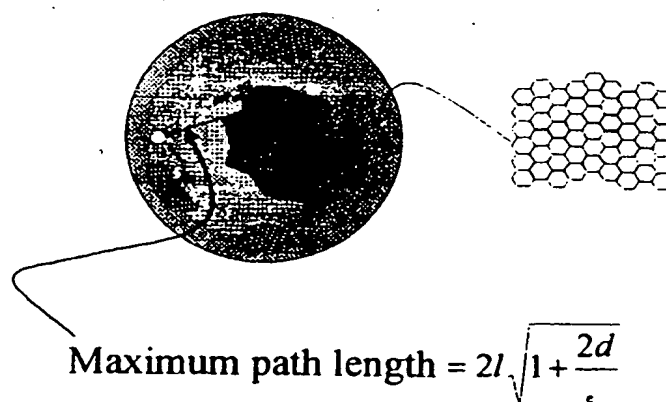
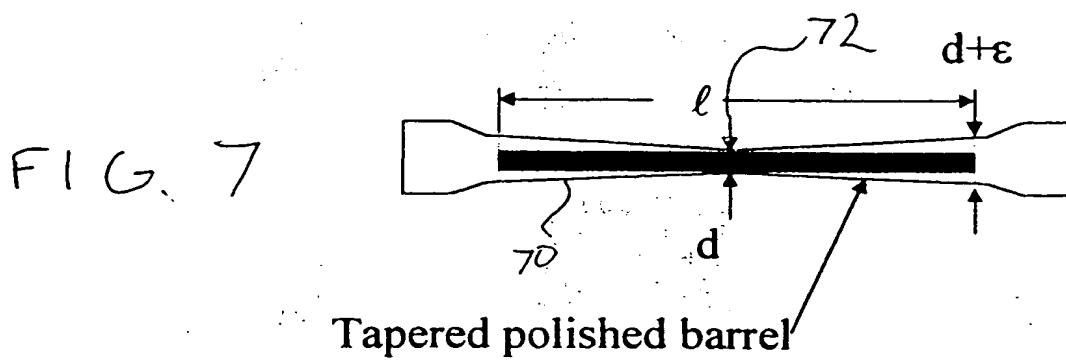
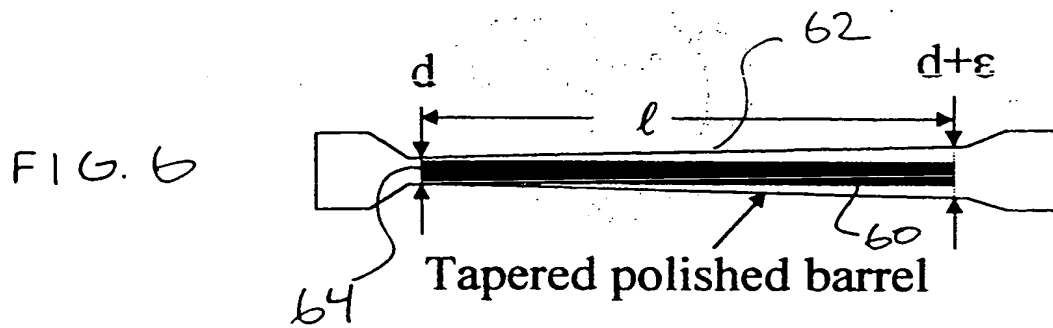
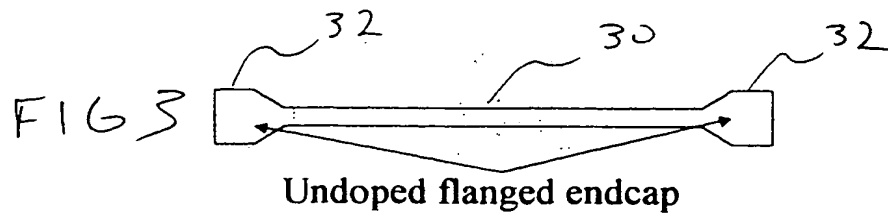


FIG. 5





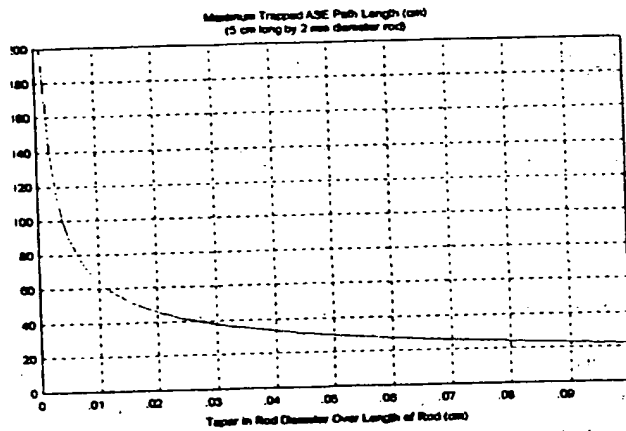


FIG. 8

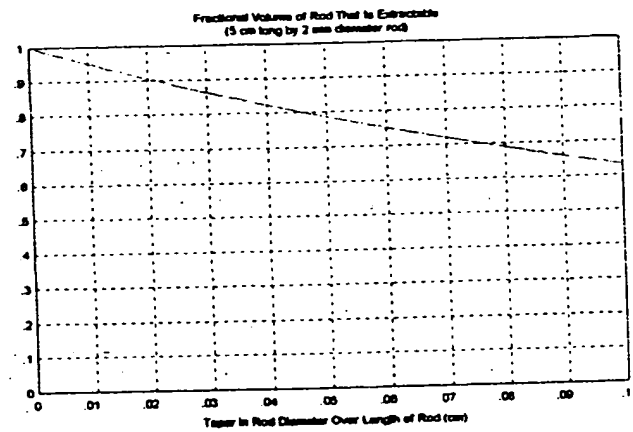


FIG. 9

INTERNATIONAL SEARCH REPORT

International Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01S3/06 H01S3/0941

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	BIBEAU C ET AL: "HIGH-AVERAGE-POWER 1-MUM PERFORMANCE AND FREQUENCY CONVERSION OF A DIODE-END-PUMPED YB: YAG LASER" IEEE JOURNAL OF QUANTUM ELECTRONICS,US,IEEE INC. NEW YORK, vol. 34, no. 10, 1 October 1998 (1998-10-01), pages 2010-2019, XP000786791 ISSN: 0018-9197 page 2014, paragraph IV	1-20
A	US 4 918 703 A (KUKLA MARK J) 17 April 1990 (1990-04-17) the whole document	1,12,16
A	US 3 513 402 A (MARRISON WARREN A) 19 May 1970 (1970-05-19) figure 1	1
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☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents:

- *A* document defining the general state of the art which is not considered to be of particular relevance
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Date of the actual completion of the international search

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INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 00/26421

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P, A	<p>DE 198 19 707 A (DAIMLER CHRYSLER AG) 11 November 1999 (1999-11-11)</p> <p>the whole document</p>	<p>1-5, 8-10, 12-19</p>

INTERNATIONAL SEARCH REPORT

Information on patent family members

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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		JP 2301177 A	13-12-1990
		JP 2947854 B	13-09-1999
US 3513402 A	19-05-1970	NONE	
DE 19819707 A	11-11-1999	NONE	

1. The first part of the document discusses the importance of maintaining accurate records of all transactions and activities. It emphasizes that proper record-keeping is essential for transparency and accountability, particularly in financial matters. The text suggests that organizations should implement robust systems to track income, expenses, and assets, ensuring that all data is up-to-date and easily accessible.

2. The second section focuses on the role of internal controls in preventing fraud and mismanagement. It highlights that strong internal controls are not only a defense against external threats but also a means to ensure the integrity of internal operations. The document recommends that organizations should regularly review and update their internal control systems to adapt to changing risks and regulatory requirements.

3. The third part of the document addresses the importance of communication and collaboration within an organization. It states that effective communication is key to ensuring that all team members are aligned with the organization's goals and objectives. The text encourages the use of various communication channels, including meetings, reports, and digital tools, to facilitate the exchange of information and ideas.

4. The fourth section discusses the need for continuous improvement and innovation. It argues that organizations should not be satisfied with the status quo but should actively seek ways to enhance their performance and efficiency. This involves fostering a culture of innovation where employees are encouraged to propose new ideas and solutions to existing problems.

5. The fifth part of the document touches upon the importance of ethical considerations in business operations. It stresses that organizations have a responsibility to act ethically and transparently, not only to their stakeholders but also to the wider community. The text suggests that organizations should establish clear ethical guidelines and ensure that all employees are trained to understand and adhere to these principles.

6. The sixth section discusses the importance of risk management. It states that organizations should identify potential risks early on and develop strategies to mitigate them. This involves a thorough assessment of both internal and external risks, followed by the implementation of appropriate risk management measures to minimize the impact of any potential adverse events.

7. The seventh part of the document focuses on the importance of financial management. It emphasizes that sound financial management is crucial for the long-term sustainability of an organization. The text recommends that organizations should maintain a healthy balance sheet, manage their cash flow effectively, and invest wisely to ensure their financial stability and growth.

8. The eighth section discusses the importance of human resources management. It states that organizations should invest in their employees, providing them with the necessary training and development opportunities to enhance their skills and productivity. The text also emphasizes the importance of creating a positive work environment that fosters employee engagement and loyalty.

9. The ninth part of the document touches upon the importance of legal compliance. It stresses that organizations must stay up-to-date with the latest laws and regulations to avoid legal penalties and reputational damage. The text suggests that organizations should consult with legal experts to ensure that all their operations are in full compliance with the applicable legal framework.

10. The final section of the document provides a summary of the key points discussed and offers some concluding thoughts. It reiterates the importance of maintaining accurate records, implementing strong internal controls, fostering effective communication, pursuing continuous improvement, acting ethically, managing risks, managing finances, and investing in human resources. The text concludes by expressing confidence that these practices will lead to the success and growth of the organization.

CORRECTED VERSION

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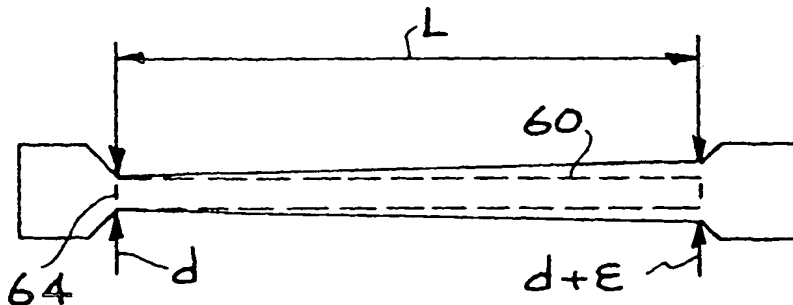
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(54) Title: TAPERED LASER ROD



(57) Abstract: Laser rods with polished barrels and flanged end caps have found increasing application in diode array end-pumped laser systems. The polished barrel of the rod serves to confine diode array pump light within the rod. In systems utilizing an end-pumping geometry and such polished barrel laser rods, the pump light that is introduced into one or both ends of the laser rod, is ducted down the length of the rod via the total internal reflections (TIRs) that occur when the light strikes the

rod's barrel. A disadvantage of using polished barrel laser rods is that such rods are very susceptible to barrel mode paths that can trap spontaneous emission over long path lengths. This trapped spontaneous emission can then be amplified through stimulated emission resulting in a situation where the stored energy available to the desired lasing mode is effectively depleted, which then negatively impacts the laser's performance, a result that is effectively reduced by introducing a taper onto the laser rod.

WO 01/024325 A1

TAPERED LASER RODS

This application claims priority to Provisional Patent Application Serial No. 60/156,279, titled "Tapered Laser Rods as a Means of Minimizing the Path Length of Trapped Barrel Mode Rays," filed September 27, 1999, incorporated herein by reference.

The United States Government has rights in this invention pursuant to Contract No. W-7405-ENG-48 between the United States Department of Energy and the University of California for the operation of Lawrence Livermore National Laboratory.

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to means for improving laser performance through reduction of amplified spontaneous emission (ASE), and more particularly, it relates to the use of a flanged and tapered laser rod to limit the maximum ray paths that can be trapped within the laser rod.

Description of Related Art

As early as 1965, reports in the literature discuss the impact of trapped light in polished barrel laser rods (J. Linn and J. Free, "Effect of Trapped Light on the Output of a Ruby laser," Applied Optics, 4, p 1099, 1965). The established picture of trapped laser light 10 in a polished barrel laser rod 12 is shown in Figure 1. Nearly all laser rods employed in laser systems today incorporate fine grind on the side surfaces of the laser rod to disrupt and scatter the barrel modes. The new approach described herein functions with an optical polish on the side surfaces of

the laser rod and instead sweeps the barrel mode light to the one of the ends of the laser rod, where it is ejected.

Trapped by total-internal-reflection (TIR), light can swirl around the inside of the laser rod and travel over long path lengths before reaching the end of the rod. The result of these long trapped ASE paths is that the gain present in the outer portion of the laser rod can be effectively depleted. If n_r is the refractive index of the laser rod and n_s is the refractive index of the material surrounding the laser rod, then it can be shown that the annular portion of the rod swept out by these swirling rays is given by $(n_s/n_r) r_{rod} < r < r_{rod}$. This means that if the gain depletion is severe, then only that portion of the rod lying inside a circular area with radius $(n_s/n_r)r_{rod}$ is useful for extracting laser energy from the rod. Figure 2 illustrates the useful laser energy extraction area 20 and the unusable area 22.

As an example, consider a YAG rod surrounded by water for cooling, where $n_r=1.82$ and $n_s=1.33$. In this case, if the swirling rays cause severe gain depletion, then only that portion of the rod contained within the central 53% ($=100(1.33/1.82)^2$) of the rod's cross sectional area would be useful for contributing to laser output power.

One technique that has recently been developed and demonstrated, the flanged end-capped laser rod See U.S. Patent No. 5,936,984, "Laser Rods With Undoped, Flanged End-Caps," by Helmuth Meissner et al., incorporated herein by reference), has proven useful in limiting the maximum length of the ray path that can be trapped in the laser rod. In the case of the straight barrel polished laser rod shown in Figure 1 above, if the swirling rays of light wander to the end of the laser rod and then strike the end face of the rod at a high angle, they will be completely trapped by total internal reflection at that end face. In such a situation, the rays will be simply turned around and sent swirling down the rod in the other direction until they hit the output face at that end. This process is particularly bad from the

viewpoint of depleting the stored laser energy in the rod, as these trapped rays now have an infinitely long trapped path length.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a technique for reducing the ability of the trapped spontaneous emission to negatively impact laser performance through amplified spontaneous emission (ASE).

It is another object of the invention to provide a tapered laser rod having flanged endcaps to dramatically reduce the maximum trapped path length of barrel modes within the laser rod.

These and other objects of the invention will be apparent to those skilled in the art based on the teachings herein.

A flanged endcap effectively traps the swirling ASE rays, causing them to be scattered out of the laser rod. However, limiting the trapped ray paths to one pass down the length of the laser rod can still allow for very long ray paths to be trapped, causing gain depletion in the laser rod. The present invention limits the maximum ray paths that can be trapped within the laser rod by tapering the laser rod over its length. This tapered design combined with flanged endcaps eliminates deleteriously long trapped path lengths.

Tapering the diameter of the laser rod over its length thus reduces the maximum trapped path length of barrel modes, reducing the ability of the trapped spontaneous emission to negatively impact laser performance through amplified spontaneous emission. In the present invention, a laser rod incorporates both undoped flanged endcaps and a tapered barrel.

In one embodiment, the rod barrel tapers in diameter from a small value of at one end to a larger value at the other end. By introducing a taper on the barrel of the laser rod, swirling rays are prevented from loitering for extended path lengths in the laser rod. This is a significant improvement over the use of the

flanged endcaps on a straight barreled rod, as the straight barrel rod configuration still allows trapped paths with infinite length.

Due to the rod's taper, there is a portion of the laser rod's volume that will be inaccessible to an extracting laser beam due to the aperture introduced by the small end of the laser rod. Because this inaccessible volume grows as the taper grows, there will be an optimum taper value.

In another embodiment, the center of the laser rod is the narrowest and the diameter increases towards either end. The advantage of this geometry, with its dual taper, over a rod with a continuous taper from one end to the other, is that the maximum trapped path length in this rod is halved compared to that in the continuously tapered rod.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates swirling rays propagating to the end of a barrel laser rod.

Figure 2 illustrates the useful laser energy extraction area and the unusable area.

Figure 3 shows a diagram of a straight barreled laser rod having a flange on each end.

Figure 4 shows a sketch of a laser rod incorporating both undoped flanged endcaps and a tapered barrel.

Figure 5 illustrates that in the use of the method of images, rays are straight-line propagated through reflective interfaces into image regions that are constructed from the original laser rod through the use of repeated reflections of the gain volume at the TIR surfaces.

Figure 6 shows the central area of the rod that can be extracted with a laser beam in a conventional resonator.

Figure 7 shows the center of the rod is the narrowest and the diameter increases as you go towards either end.

Figure 8 shows the maximum trapped ASE path length versus taper in rod diameter over the rod length.

Figure 9 shows the fractional volume of the rod that is extractable versus taper in rod diameter over the rod length.

DETAILED DESCRIPTION OF THE INVENTION

The present inventors have discovered that once the swirling rays shown Figure 1 reach the end of the barrel laser rod, the placement of a flanged endcap will effectively trap the rays and they will be scattered out of the laser rod. Figure 3 shows a diagram of a laser rod 30 having a flange 32 on each end. Such configuration has been shown to be effective at limiting the maximum ray paths that can be trapped in the laser rod.

Effectively, the flanged laser rod limits the swirling rays described above to at most one pass down the length of the laser rod. However, even limiting the trapped ray paths to one pass down the length of the laser rod can still allow for very long effective ray paths to be trapped, which in turn can pose a serious problem for gain depletion in the laser rod. These long trapped ray paths are characterized by swirling around many times while only moving a very short transverse distance up or down the laser rod. In fact, it is still possible for infinitely long ray paths to exist, which swirl around the laser rod but do not walk up or down its length.

The present invention limits the maximum ray paths that can be trapped within the laser rod by tapering the laser rod over its length. This tapered design

combined with the use of the flanged endcaps described above results in the elimination of the possibility of infinitely long trapped path lengths.

Tapering the diameter of the laser rod over its length dramatically reduces the maximum trapped path length of a barrel mode, thereby reducing the ability of the trapped spontaneous emission to negatively impact laser performance through amplified spontaneous emission (ASE). Figure 4 shows a sketch of a laser rod incorporating both undoped flanged endcaps and a tapered barrel, which is the subject of the presently disclosed invention.

In Figure 4, the rod barrel 40 tapers in diameter from a small value of d at one end to a larger value of $d+\epsilon$ at the other end 44. The impact of introducing a taper on the barrel of the laser rod is that it prevents swirling rays from loitering for extended path lengths in the laser rod. This is a significant improvement over the use of the flanged endcaps on a straight barreled rod, as the straight barrel rod configuration still allows trapped paths with infinite length. To estimate the maximum path lengths that can be trapped by a tapered laser rod with endcaps, a simple "method of images" technique can be invoked that greatly simplifies the calculation. The reason for using the method of images trick is that it simplifies the calculation of ray paths that involve TIR. Using the method of images, rather than having to calculate reflected angles and multiple bounce paths, rays are just straight-line propagated through reflective interfaces into image regions that are constructed from the original laser rod through the use of repeated reflections of the gain volume at the TIR surfaces. Of course, using this method does require that the constructed image space be continuous in the sense of not containing any internal gaps. Unfortunately, round cross-sectioned rods do not meet the requirement of continuously filling a region of space on reflection about their various TIR surfaces. One simple approximation that allows the method of images to be applied to round rods models them as having a hexagonal cross-section. Under this approximation,

a rod with a taper generates a spherical shell with thickness equal to the length of the rod.

In Figure 5, the longest path length that is trapped in the laser rod is then the length of the longest line that can be drawn between any two points on the surface of the sphere. In the figure, a ray which intersects the surface of the sphere corresponds to a trapped ray which has wandered into the flanged endcap at the rod end with the largest diameter. With the help of Figure 5, the longest trapped ray path is seen to correspond to a line that is tangent to the surface of the inner sphere. A simple calculation for the presently considered rod, with its diameter tapering from d at one end to $d+\epsilon$ at the other, then gives the length of this longest trapped path length as $2\ell\text{SQR}(1+2d/\epsilon)$, where ℓ is the length of the laser rod over which the taper occurs. Considering this expression for the longest trapped ray length, the question that naturally arises is what is the optimum value for the taper parameter ϵ . Clearly, if ϵ approaches 0, then the maximum path length can be pushed to infinity as has already been discussed for a straight rod. On the other hand, if ϵ is made too large, then the useful mode volume of the rod is decreased. This last point is illustrated with the help of Figure 6 as discussed below.

In Figure 6, the central area 60 corresponds to that portion of the rod 62 that can be extracted with a laser beam in a conventional resonator. Due to the rod's taper, there is a portion of the laser rod's volume that will be inaccessible to an extracting laser beam due to the aperture introduced by the small end 64 of the laser rod. Because this inaccessible volume grows as the taper grows, there will be an optimum taper value, ϵ , that best balances the contradictory requirements of maximizing the size of the taper so as to minimize the longest trapped path length, and minimizing the size of the taper so as to maximize the fractional volume in the rod that is accessible to the extracting laser beam. Figures 8 and 9 show these two

quantities plotted against the taper size for a 2 mm diameter by 5 cm long Yb:YAG laser rod.

A variation on the above approach that offers some performance benefit is shown in Figure 7. Here, rather than having a continuous taper over the entire length of the laser rod 70, the center of the rod 72 is the narrowest and the diameter increases as you go towards either end.

The advantage of this geometry, with its dual taper, over a rod with a continuous taper from one end to the other, is that the maximum trapped path length in this rod is halved compared to that in the continuously tapered rod. Additionally, this halving of the maximum trapped path length comes without a penalty in the fractional volume of the rod from which energy can be extracted, assuming the same value of taper parameter, ϵ , for both types of rods.

The foregoing description of the invention has been presented for purposes of illustration and description and is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations are possible in light of the above teaching. The embodiments were chosen and described to best explain the principles of the invention and its practical application to thereby enable others skilled in the art to best use the invention in various embodiments and with various modifications suited to the particular use contemplated. The scope of the invention is to be defined by the following claims.

We claim:

1. An apparatus, comprising:
 - a polished laser rod comprising a first end and a second end, wherein said laser rod comprises a tapered diameter;
 - a first flanged endcap operatively connected to said first end;
 - and
 - a second flanged endcap operatively connected to said second end.
2. The apparatus of claim 1, wherein said laser rod comprises a maximum diameter at said first end and a minimum diameter at said second end.
3. The apparatus of claim 1, wherein said laser rod comprises a maximum diameter at said second end and a minimum diameter at said first end.
4. The apparatus of claim 1, wherein said laser rod comprises a minimum diameter at about half the distance from said first end to said second end.
5. The apparatus of claim 1, wherein said first flanged endcap and said second flanged endcap are undoped.
6. The apparatus of claim 1, wherein said laser rod tapers in diameter from a small value of d at one end to a larger value of $d+\epsilon$ at the other end.
7. The apparatus of claim 1, wherein said tapered diameter is optimized to a taper value that balances the contradictory requirements of maximizing the size of said taper so as to minimize the longest trapped path length of light rays propagating within said laser rod, and minimizing the size of said taper so as to maximize the fractional volume in said laser rod that is accessible to an extracting laser beam.

8. The apparatus of claim 1, wherein said tapered diameter continuously continuous changes over the entire length of said laser rod.

9. The apparatus of claim 1, wherein said laser rod is narrowest between the ends of said laser rod and the diameter increases at each end.

10. The apparatus of claim 1, wherein said laser rod is narrowest at about half the distance between the ends of said laser rod and the diameter increases as you go towards either end.

11. The apparatus of claim 10, wherein said tapered diameter is optimized to a taper value that balances the contradictory requirements of maximizing the size of said taper so as to minimize the longest trapped path length of light rays propagating within said laser rod, and minimizing the size of said taper so as to maximize the fractional volume in said laser rod that is accessible to an extracting laser beam.

12. A solid state laser, comprising:

- a laser rod with a first end and a second end, wherein said laser rod comprises a tapered diameter;
- a first flanged, undoped end-cap optically contacted to said first end portion to form a first interface;
- a second flanged, undoped end-cap optically contacted to said second end to form a second interface;
- a cooling jacket sealably coupled to said first and second flanged end-caps;
- a pump laser for providing pump laser light directed at said first flanged end-cap; and
- a lens duct interposed between said pump laser and said first flanged end-cap, wherein said lens duct will concentrate said pump laser light.

13. The solid state laser of claim 12, wherein said laser rod has a host lattice, and wherein said host lattice and said first and second flanged end-caps are selected from the group consisting of yttrium aluminum garnet, gadolinium gallium garnet, gadolinium scandium gallium garnet, lithium yttrium fluoride, yttrium vanadate, phosphate glass and sapphire.

14. The solid state laser of claim 13, wherein said host lattice is doped with a material selected from the group consisting of Ti, Cu, Co, Ni, Cr, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm and Yb.

15. The solid state laser of claim 12, wherein said laser rod comprises Yb.sup.3+ doped YAG, and wherein said pump laser is an InGaAs diode laser array.

16. A method for fabricating a laser rod, comprising:
providing a polished laser rod comprising a first end and a second end;
operatively connecting a first flanged endcap to said first end;
operatively connecting a second flanged endcap to said second end;
and
tapering the diameter of said laser rod.

17. The method of claim 16, wherein the step of tapering the diameter of said laser rod comprises forming a maximum diameter at said first end and a minimum diameter at said second end.

18. The method of claim 16, wherein the step of tapering the diameter of said laser rod comprises forming a maximum diameter at said second end and a minimum diameter at said first end.

19. The method of claim 16, the step of tapering the diameter of said laser rod comprises forming a minimum diameter at about half the distance from said first end to said second end.

20. The method of claim 16, further comprising optimizing the diameter of said laser rod to a taper value that balances the contradictory requirements of maximizing the size of said taper so as to minimize the longest trapped path length of light rays propagating within said laser rod, and minimizing the size of said taper so as to maximize the fractional volume in said laser rod that is accessible to an extracting laser beam.

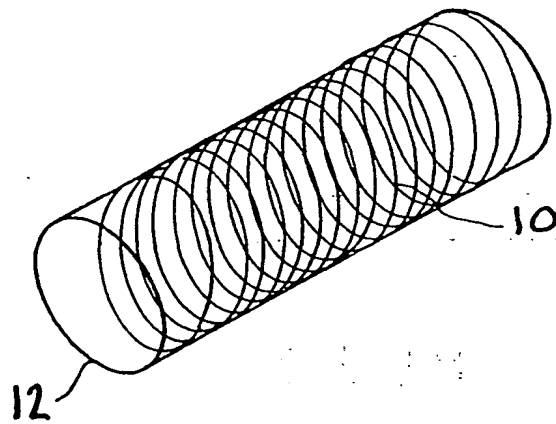


FIG. 1

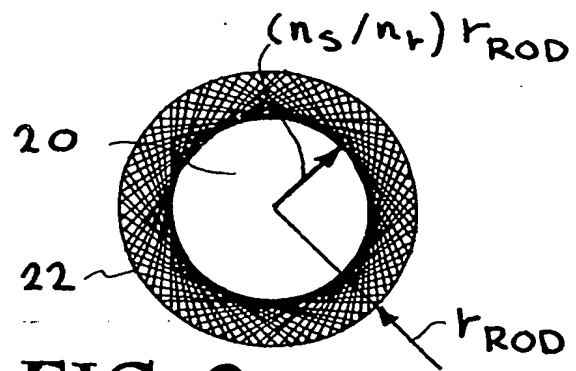


FIG. 2

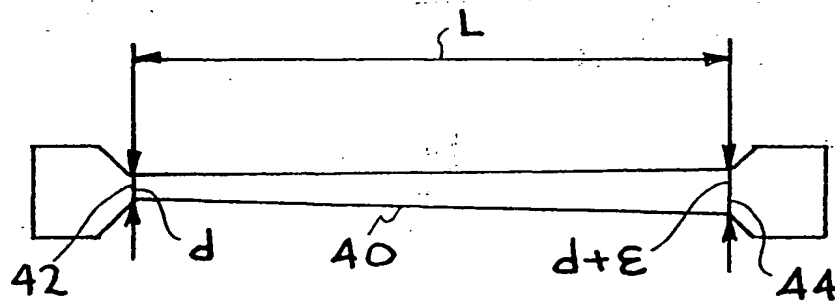


FIG. 4

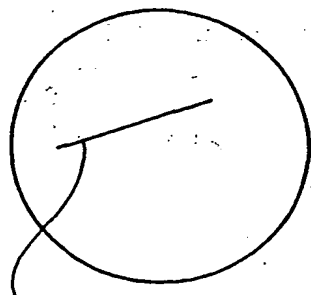
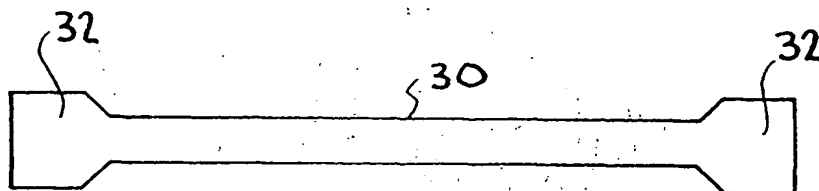
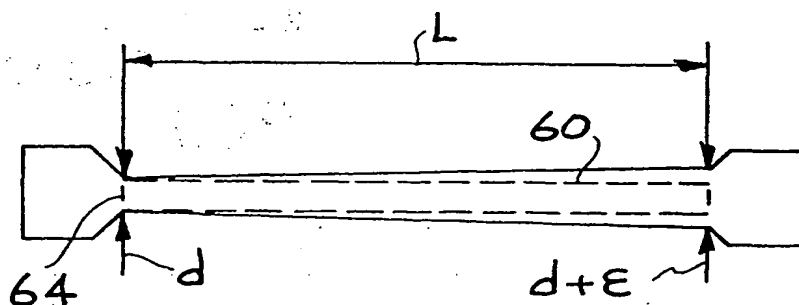
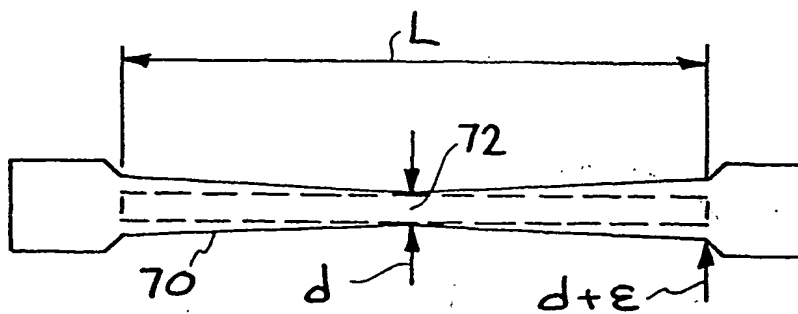


FIG. 5

$$\text{MAXIMUM PATH LENGTH} = 2L \sqrt{1 + \frac{2d}{\epsilon}}$$

**FIG. 3****FIG. 6****FIG. 7**

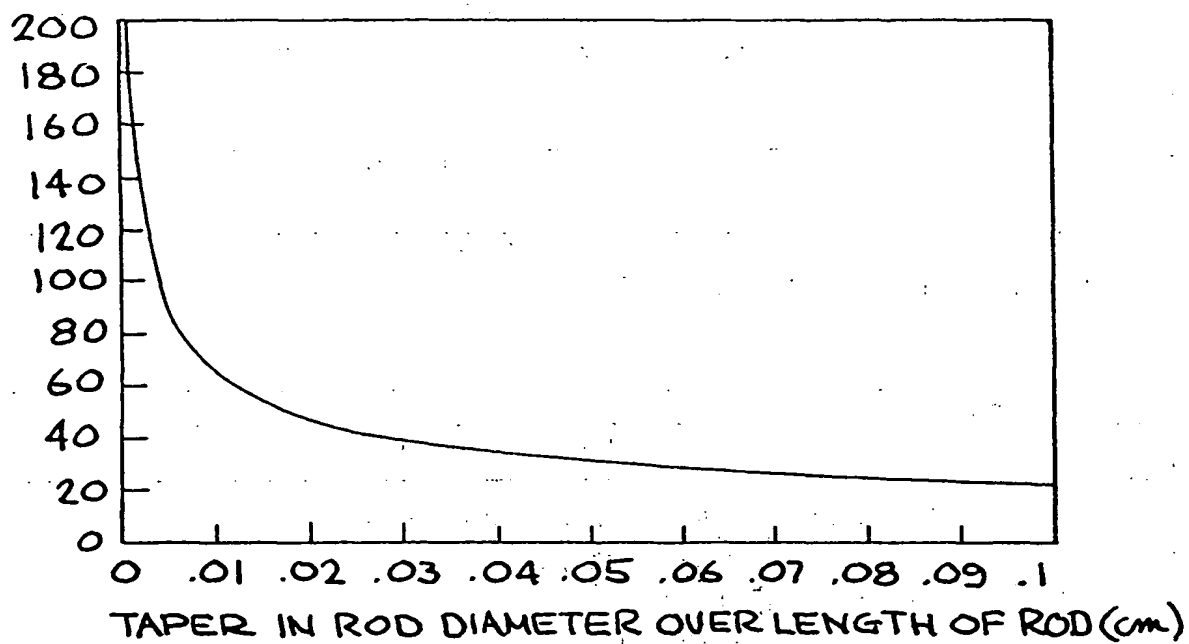


FIG. 8

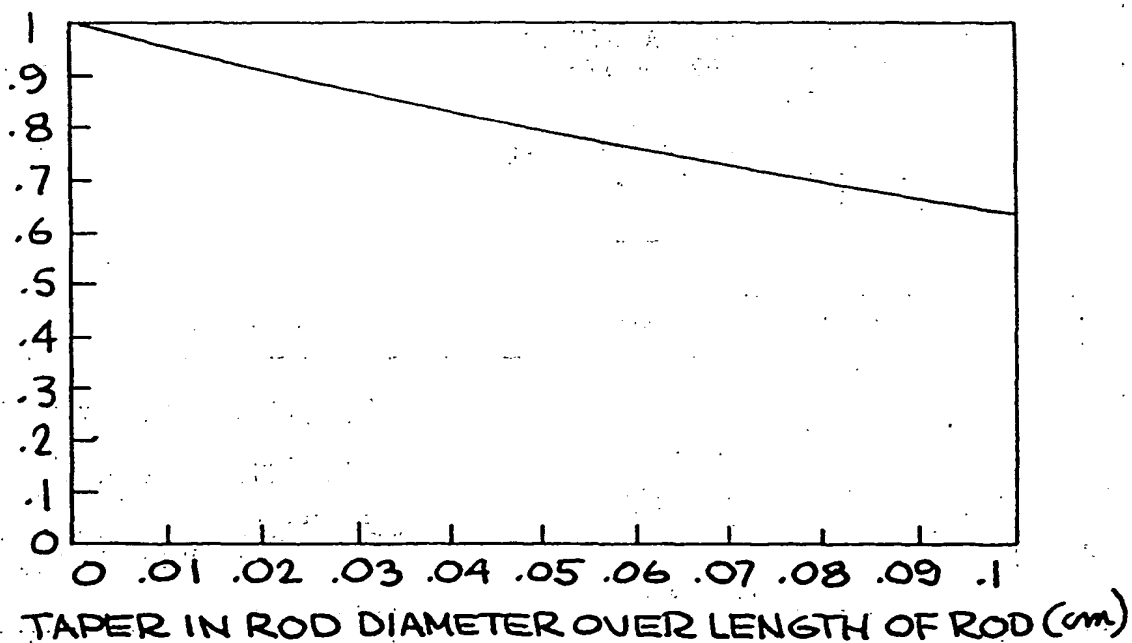


FIG. 9

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 00/26421A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01S3/06 H01S3/0941

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	BIBEAU C ET AL: "HIGH-AVERAGE-POWER 1-MUM PERFORMANCE AND FREQUENCY CONVERSION OF A DIODE-END-PUMPED YB: YAG LASER" IEEE JOURNAL OF QUANTUM ELECTRONICS, US, IEEE INC. NEW YORK, vol. 34, no. 10, 1 October 1998 (1998-10-01), pages 2010-2019, XP000786791 ISSN: 0018-9197 page 2014, paragraph IV	1-20
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☒ Further documents are listed in the continuation of box C.☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

20 February 2001

Date of mailing of the international search report

28/02/2001

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Galanti, M

INTERNATIONAL SEARCH REPORT

Application No
PCT/US 00/26421

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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